

## Full-Length Article

**Music, Maestro, Please: Thalamic Multisensory Integration in Music Perception, Processing and Production**Artur C. Jaschke<sup>1,2,3</sup><sup>1</sup>Department of Music Therapy, ArtEZ University of the Arts, Enschede, The Netherlands<sup>2</sup>Department of Neonatology, University Medical Center Groningen, Groningen, The Netherlands<sup>3</sup>Department of clinical Neuropsychology, VU Amsterdam, Amsterdam, The Netherlands**Abstract**

Music activates a wide array of brain areas involved in varying functions such as perception, processing and execution of music. Understanding musical processes in the brain has multiple implications in the neurologic and health sciences.

Challenging the brain with a multisensory stimulus such as music activates responses beyond the auditory cortex of the temporal lobe. Other areas that are involved include the frontal lobes, parietal lobes, areas of the limbic system such as the amygdala, hippocampus and thalamus, the cerebellum and the brainstem. Nonetheless, there has been no attempt to summarize all involved brain areas in music into one overall encompassing map. This may well be, as there has been no thorough theory introduced, which would allow an initial point of departure in creating such a map. Therefore, a thorough systematic review has been conducted to identify all mentioned neural connections involved in the perception, processing and execution of music.

Communication between the thalamic nuclei is the initial step in multisensory integration, which lies at the base of the neural networks as proposed in this paper. Against this background, this manuscript introduces what is, to our knowledge, the first map of all brain regions involved in the perception, processing and execution of music. Consequently, placing thalamic multisensory integration at the core of this atlas allowed us to create a preliminary proposal of a concept theory to explain the complexity of music induced brain activation, something that we speculate, will ultimately require thorough investigation and substantiation through neuroimaging and neurophysiological research in the future.

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“The thalamus and its anatomical and physiological relationships to the cerebral hemispheres, we feel, is a factor of considerable importance in understanding the workings of music.”

Altshusler, 1944: p. 793 [1]

Music activates a wide array of brain areas involved in different functions such as the perception, processing, and execution of music.[2-12] Understanding musical processes in the brain has multiple implications in the neurologic and health sciences; as for example neural networks involved in Parkinson’s Disease,[13] Autism spectrum Disorders [14,15] neural plasticity enhancement in different populations [12, 16] stroke recovery[17] or research analysing resting state

networks.[18] Understanding the networks music can trigger, therefore, provides immediate applications into the use of music-related interventions (educational as well as therapeutic) in a wide array of clinical and non-clinical populations.

Brain imaging techniques such as functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI), have given new insights into this functionality and the inter-connectivity of involved brain areas. [2,8,10,12,19] Engaging the brain with a multisensory stimulus such as music, activates responses beyond the auditory cortex in the temporal lobe, which is associated as the main processor of auditory stimuli[19]. Brain networks involving the frontal lobes, [8,20,21] parietal lobes,[8,11] the limbic system such as the amygdala, hippocampus and thalamus, [21,22] the cerebellum [23] and the brainstem[10]. Nonetheless, there has been no attempt to summarise all involved brain areas in music into one overall encompassing map. This may well be, as there has been no thorough theory introduced, which would provide a baseline for an initial point of departure in creating such a map.

To understand the rationale behind the forthcoming, presented map, a closer look at what the term ‘music’ actually

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International Association for Music &amp; Medicine (IAMM).

encompasses is needed. Music is comprised several sub-components or dimensions: being melody, rhythm, beat, timbre, harmony, pitch, spatial acoustics and the combination of all of these. All of these sub-components define music and what we understand music to be, from a listener's point of view. Because of this variety in terms of listening, the brain needs multiple brain regions to make sense of the here-presented term 'music.' Additionally, music has the ability to induce emotions that relate to our well-being. Music triggers multiple brain regions that are necessary, not only to make sense of the musical components themselves, but additional networks interlinked with executive functions, emotions, memory, higher brain functions and even the oldest structures of our evolved brain, the limbic system. Music with its different facets therefore can be seen as a multisensory stimulus in light of the above-mentioned diverse response-related activations in the brain. When this musical stimulus is traced from the cochlea to all involved brain regions, neural networks lead exclusively through the thalamic nuclei [24,25]. Here the stimulus is pre-processed through a communication between the auditory, the visual, somatosensory, premotor and motor, higher order multisensory and 'non-specific' thalamic nuclei, before it is 'sent out' to be further processed in the relevant brain area.[24,26,28] This communication between the thalamic nuclei involved in auditory, sensory, motor and higher order information processing is the initial step in multisensory integration, which lies at the base of the neural network map as proposed in this paper. Perception and performance of music have been widely accepted by the neuroscientific community as being multisensory by nature[27]. As stated above, we define music as a multisensory stimulus as the processing of music requires more than just auditory networks but reaches as far as deep brain structures and their connectivity with higher order functions. Expanding on this concept we can furthermore argue that the perception, processing and execution of music is based on these multisensory integration processes. Placing this theory at the centre of a detailed map of involved brain structures in music, consequently, sets the tune in its creation. Koelsch[8], has recently summarised neural networks involved in the perception of music, however has focused more on the effects of this stimulus with implications to involved neural structures rather than creating a thorough overview of engaged areas, with multisensory integration of music at its core. Altenmüller and Schlaug[21] have further addressed the importance of understanding these networks, by arguing the correlates of music involved in brain processes related to health and wellbeing. Against this backdrop, this paper introduces the to our knowledge first thorough map of all involved brain regions in the perception, processing and execution of music, out of the general need of such a map and the knowledge, which can be gained from it. Consequently, placing thalamic multisensory integration at the core of this map, allowed to create a preliminary theory to explain the

complexity of music induced brain activation, ergo a consecutive network encompassing and explaining the connections between all areas and not only areas of interest in music related research.

## Methods

We conducted an extensive literature search to identify all brain areas involved in the perception, processing and execution of music. Furthermore, we consulted literature, which consolidated our findings in creating our model with a multisensory thalamic integration system at its core. The following online databases were searched: PubMed/MedLine, psychINFO, ScienceDirect, Embase, ERIC, ASSIA and Jstor on neural involvement in the perception, processing and execution of music.

Where necessary, the search terms were attuned to the requirements of other databases searched. Search terms included the following steps: 1) music perception and multisensory integration, 2) music perception, processing and execution and neuroimaging, 3) thalamic multisensory integration and music perception; 4) neural network connectivity and music perception and imaging; 5) Multisensory integration and music. We further consolidated and expanded our investigation by searching with the following MeSH terms; Music, neurology, circuitry and function. We included all data, which indicated a clear effect of the involved brain regions and were published in a peer-reviewed journal. Of note, we did not set a publication date limit and have included research until March 2019. Neither have we set a lower cut-off for included articles. However, articles were not older than 1995 as this point marks the beginning of brain imaging in music related research.[3,4]

The circuitry map was created in Adobe® Photoshop and Adobe InDesign® 2016, by using standard illustration tools. Brain regions, connections, alternative connections and the fascicule were inserted according to the literature reviewed. After removing duplicates or studies, which have covered the same brain region or networks, 126 studies describing involved structures have been included in the creation of the here presented map, with 36 fundamental findings.

## Results

Based on the literature reviewed, we were able to identify four main global systems (frontal, temporal and parietal lobe and the pre-motor and motor cortex) together with individual regions, such as the anterior cingulate cortex, the nucleus accumbens, the insula, anterior superior temporal gyrus, the superior temporal sulcus, the hippocampus, amygdala, cerebellum and the brainstem. These were connected accordingly to the literature with the thalamic nuclei. The thalamic nuclei - which lie at the center of our model - are communicating and interacting through individual

anatomically identified pathways[26]. Here we used solid and dashed arrows indicating strong connections/communications (solid arrows) and alternative or additional connections/communications (dashed arrows). Arrowheads indicate the direction and if the stimulus is only sent, only received or both on this particular communication pathway. Of note are black colored arrows, which always indicate the signal as it is fed forward from the thalamic nuclei and respectively, colored arrows as signals feeding back from the stimulated neural area. Furthermore, we have

incorporated the three main white matter connections, playing an important role in the perception, processing and execution of music; of note is the fasciculus longitudinalis superior[28], the arcuate fasciculus[12, 29] and the uncinate fasciculus[29] in gradient shades of grey (Figure 1). As we have aimed at presenting the results of our literature search in a visual map, we have not included Mean or Standard deviation of the reviewed literature. This choice has been made as the statistical values do not represent connectivity to the thalamic nuclei at this stage of the presented article.

**Neural network of involved brain areas in music;  
with thalamic multisensory integration at its core.**

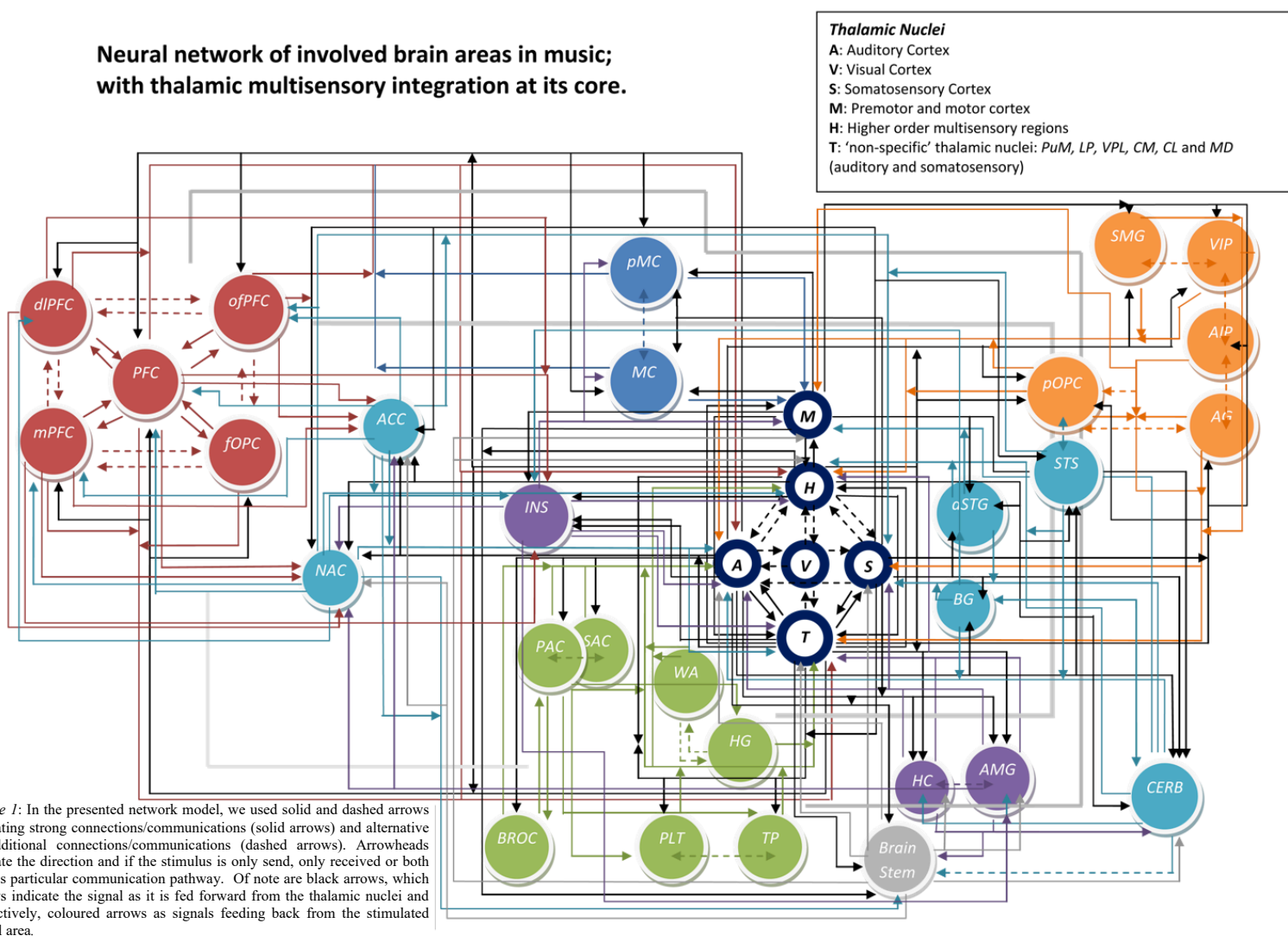
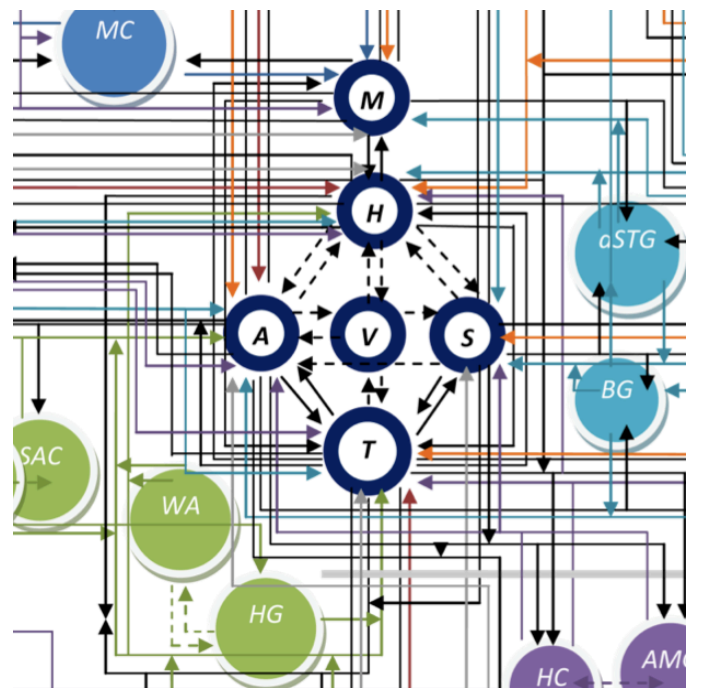


Figure 1: In the presented network model, we used solid and dashed arrows indicating strong connections/communications (solid arrows) and alternative or additional connections/communications (dashed arrows). Arrowheads indicate the direction and if the stimulus is only sent, only received or both on this particular communication pathway. Of note are black arrows, which always indicate the signal as it is fed forward from the thalamic nuclei and respectively, colored arrows as signals feeding back from the stimulated neural area.

**Figure 1:** Neural network map of all involved brain areas in the perception, processing and execution of the musical stimulus.

### Thalamic Nuclei

The interconnection between the 6 main thalamic nuclei was established from Wang et al's [30] proposed influence of a perceptual task on neural responses. These thalamic nuclei are subdivided into specific auditory, visual, somatosensory and motor nuclei with additional nuclei sending and receiving stimuli of higher order multisensory regions and so-called 'non-specific' thalamic nuclei. These 'non-specific' nuclei create additional connections and docking points for auditory and somatosensory information through the medial pulvinar nucleus (PuM), lateral posterior (LP), ventral posterior lateral (VPL), centro medial (CM), centro lateral (CL) and medial dorsal (MD) nuclei. [24,25,31] Connections between the auditory, visual, motor, somatosensory and higher order regions are given through the 'non-specific' thalamic nuclei. These connections are further strengthened through interconnectivity of the here-described individual nuclei, creating an intriguing and complex web at onset of our model. Nonetheless, this complex intercommunication is fundamental for the further understanding of how the here proposed mapping is inter-connected; thus, receiving the 'raw' musical stimulus before feeding it forward and receiving it back (Figure 2). The interactions between the nuclei are an intriguing process in the thalamus. More so is the question not yet answered, which role the different thalamic nuclei play in the perception of music. As mentioned above, there are different dimensions of music perception and several attributes that make music. The Thalamic Nuclei have to play an important role as this stimulus is multisensory. Which role however, in terms of beat, rhythm, melody pitch and-so-forth, they are playing needs further research. Nonetheless, the here presented hypothesis may be seen as the initial step in researching the interrelation of music as well as thalamic nuclei networks. Additionally, a recent study, [31] has reported that the thalamic nuclei with their respective networks, serve additional roles in the thalamo-cortico-thalamic loop of incoming sensory stimuli to for example the prefrontal cortex. The authors argue, that the role of the thalamus to cognitive functions, such as executive functioning, that are highly active during music-related tasks, has been underestimated and has shown thalamic control of cortical connectivity outside of its relaying function, questioning the role of the thalamus in general.

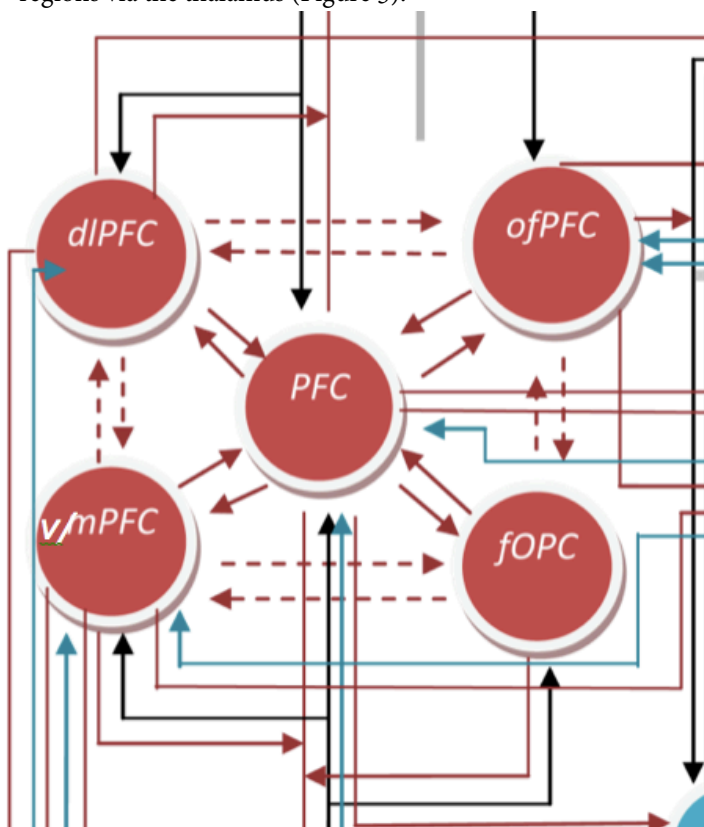


**Figure 2:** The thalamic Nuclei: Premotor and Motor Cortex; Higher order multisensory regions; Visual Cortex; Somatosensory Cortex; Auditory Cortex; Non-specific thalamic nuclei

### Frontal lobe

Communication of the frontal parts with the thalamus and additional areas of the limbic system, the anterior cingulate-cortex (ACC), the nucleus accumbens (NAC), Insula and the cerebellum are divided into three stages 1) inter-connectivity in-between the involved frontal regions, 2) feedback and feedforward pathways via the thalamic nuclei and 3) direct communication with ACC, NAC and the insula. Stage one describes the direct communication in between the pre-frontal cortex [33,34](PFC), with the dorsolateral prefrontal cortex. [33,34](dlPFC), orbitofrontal prefrontal cortex [34](ofPFC), medial prefrontal cortex [33](mPFC) and the frontal operculum [34](fOPC) while a loop is created through the auditory nuclei and the 'non-specific' thalamic nuclei as indicated in stage 2. [24,25] Through this loop, the frontal regions communicate with the hippocampus, the amygdala and the cerebellum, while additionally activating the brainstem arousal system and 'feedbacking' from the temporal lobes. The in stage 3 distinct communication in-between the ACC and the NAC is an anatomically given connection and is therefore passively activated when receiving the stimulus in the frontal regions [34]. Additionally, Broca's area is involved in recognizing possible lyrics and plays an interesting role in the differentiation of sounds. [36]

The frontal regions mainly process anticipation and expectation and the execution of musical thought during the event of listening and execution. [35] Furthermore, they relate to musical improvisation, which is also related to the amygdala and the hippocampus. Of note is the dlPFC[37], which plays a crucial role in improvisation. Furthermore, they contribute to musical learning and memory through the indicated loop connecting deeper brain regions with frontal regions via the thalamus (Figure 3).



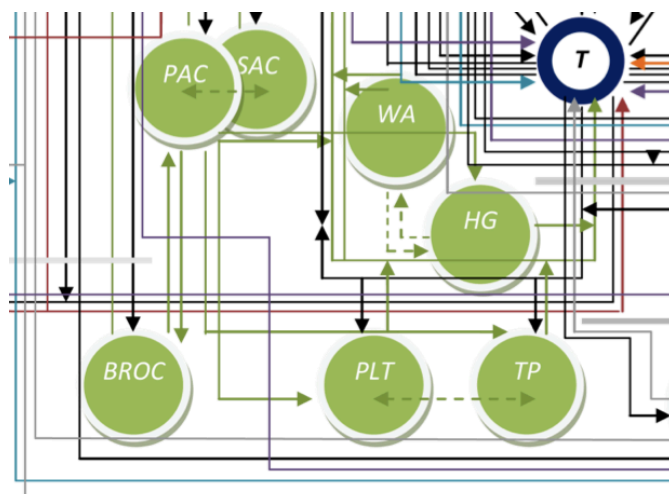
**Figure 3: Frontal Lobe:** PFC (executive functions in interconnection with the here presented sub areas) vmPFC; dlPFC (Decision making, e.g. improvisation); ofPFC (Decision making / emotion/ reward /Emotion control); mPFC (Evoked autobiographical memory); fOPC (Cognitive process control)

*Temporal lobe*

As the main region processing the incoming multisensory musical stimulus, the understanding of how music is processed is mostly consolidated in the temporal lobe. In the temporal lobes, similar to the frontal lobes, the following stages apply; 1) the connection to the thalamus in an auditory/somatosensory loop and 2) direct communication in-between involved areas in the processing and perception of the musical stimulus. The overall communication of the involved temporal areas such as the primary and secondary auditory cortex [36](PAC and SAC), Wernicke’s areas [36](WA), Heschl’s Gyrus [36](HG) and the planum Temporale [36](PLT) together with the temporal pole

[36](TP) are initially faced with the incoming raw stimulus. Through the suggested loop, information perceived in the temporal areas are communicated to other regions, where further processing takes place and several reactions to the musical stimulus, e.g. emotional reaction in the amygdala in collaboration with the PFC, ACC and NAC, can occur. The PAC and SAC are the primary preceptors of the auditory incoming information. Wernicke’s area and Heschl’s gyrus, process mimicking and associations together with pitch intervals and melody. [35,36] The planum temporale and the TP process timbre and spatial identification of sound. These functions feed constantly back to the thalamus and additionally to their role in emotional reactions, connect to motor areas and processing areas in the frontal lobe, the motor cortex, the cerebellum and brainstem. [25,34] (Figure 4)

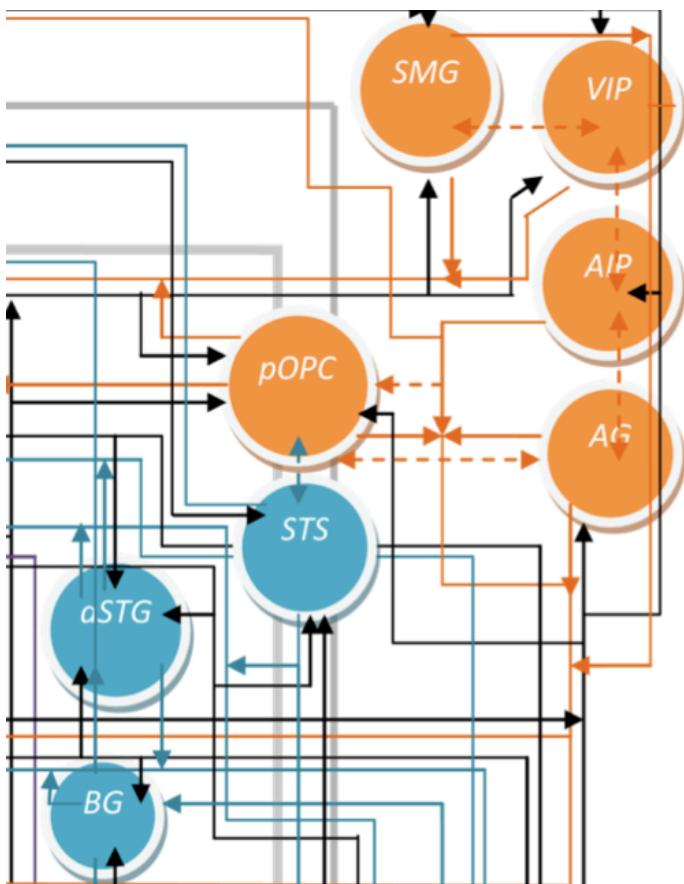
**Figure 4: Temporal Lobe:** PAC/SAC (Pitch decoding); WA (Speech identification); HG (Pitch interval and melody perception); BROCA (Language perception/interpretation. Of note, Brocas is anatomically to be found in the frontal lobe, however as there is strong interconnectivity and inter-activity to areas in the Temporal Lobe, we have decided to place it among the connectivity and activity patterns of the temporal lobe); PLT (Timbre and spatial location of sound); TP (Emotion/attention/behavior/memory)



*Parietal lobe*

Connections in the parietal lobe revolve more around the recognition of harmony, pitch intervals and patterns[36]. These connections show a strong tendency to communicate in between each other, while recruiting the superior temporal sulcus (STS) and the basal ganglia (BG) in accordance to the connections with the thalamic nuclei. These thalamic nuclei allow a connection in-between deeper cortical and sub cortical areas. Of note are the ventral and anterior intra-parietal regions, which are strongly associated with multisensory processing.[26,31] Information on the parietal lobe involvement however, still remains scarce and therefore future

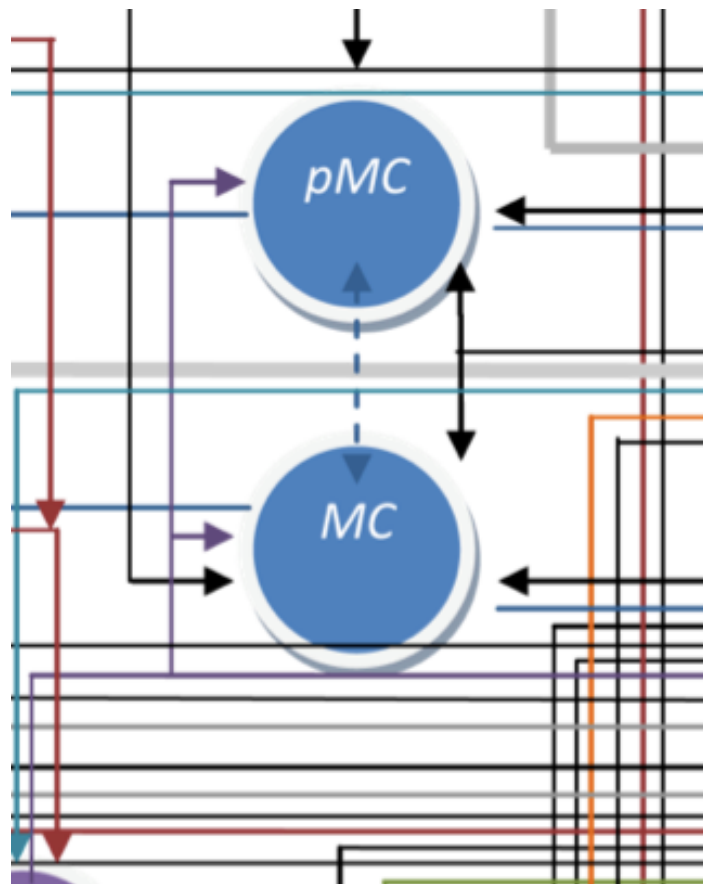
research will need to be conducted to shed light into the involvement of this region (Figure 5).



**Figure 5: Parietal Lobe:** SMG (Language perception and processing); VIP (Sensory information - visual/auditory); AIP/AG (Sensory information – sensational Shape/size/orientation/visuomotor transformation of actions); pOPC (junction of the two main fasciculi); STS (Sensory pitch pattern recognition); aSTG (Recognition of social cognition e.g. in improvisation / direct connection to primary auditory cortex/Streams of sound recognition); BG (Sensory rhythm pattern recognition/initiation of movement)

*Pre motor and motor cortex*

The motor (MC) and pre motor cortex (pMC) are major structures when it comes to the execution of music.[11] Additionally, communication with the cerebellum and the basal ganglia contribute to the perception of time and rhythm in music.[11] The MC as well as the pMC receive direct input from the premotor and motor nuclei in the thalamus and therefore connect within a constant feed forward and feedback loop to the cerebellum and the brain stem.[10] Furthermore, it receives a feed forward signal from the frontal areas. These connections however remain still speculative and further research has to show the functional connection of this system (Figure 6).



**Figure 6: Motor and Premotor Cortex:** pMC (Execution of movement); MC (planning,/execution/control of movement)

*Additional and individual areas involved in the perception, processing and execution*

The anterior cingulate-cortex (ACC), the nucleus accumbens (NUC), the insula, anterior superior temporal gyrus (aSTG), the superior temporal sulcus (STS), the hippocampus (HC), amygdala (AMG), cerebellum (CERB) and the brainstem, are brain regions, which are involved in both active and passive perception and processing of music. These regions either receive a direct input from one of the main areas to support the process of perceiving the stimulus and accordingly creating a response to it or feed back/feed forward via the thalamic nuclei. Even though their involvement is clearly visible in imaging studies [2-37], it is yet not clear if their involvement is due to the anatomical connections within the brain or if these areas play an active role in the perception and processing in music. Here again will future research illuminate the path of discovery within the neuro-musicological and music cognitive sciences (Figures 7 and 8).

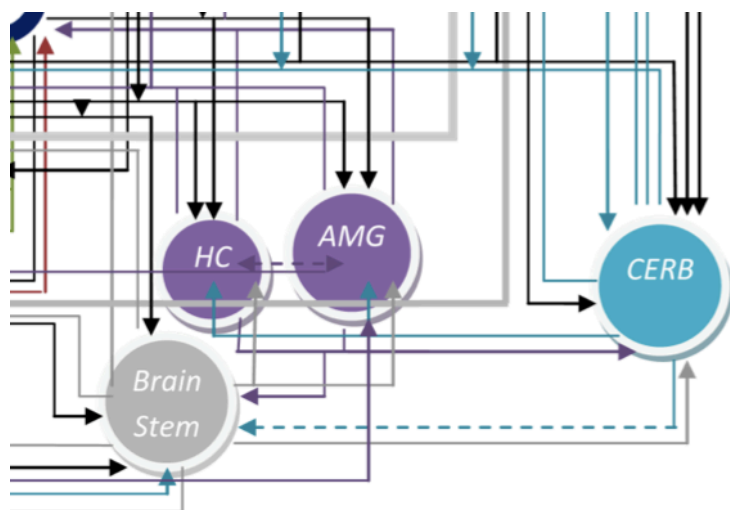


Figure 7 Additional neural structures: HC (Memory function); AMG (Emotion decoding); CERB (Movement / rhythm perception); Brain Stem (Rhythm / sensory input / arousal)

amalgamate these into a single underlying theory is not present as of yet. Defining music as multisensory and place it at the centre of a neuro-musical circuit map is an ambitious task. Nonetheless, the here introduced theorem poses the first understanding of the complex network triggered by the musical stimulus with the specific and elaborate character of thalamic nuclei. This understanding will – to say it simply – help to comprehend what effects music actually has on our neural physiology. The impact of music on different cerebral regions and areas and their interconnectivity, supports the claim of being a powerful tool when used in educational as well as therapeutic settings. Understanding the cognitive building blocks of music allows tracing the stimulus throughout the brain and enables *individual* approaches to both, therapy and education. [12, 40]

Perceiving, processing and executing music recruits more than one neural area. It is a combination of the different facets of music such as rhythm, melody, timbre etc projected onto the individual areas of the brain, which decode the musical stimulus to create what we understand as music. These areas however, are not exclusive to music. Especially areas in the temporal as well as frontal lobes are equally involved in language and arithmetic and are therefore, overlapping with the above presented music related regions. [6] Each of the regions includes its own interpretation of the task at hand and therefore stimulating these, increases more than the actual understanding of the task, but can be transferred to other mental exercises such as increase in empathy or working memory, which share overlapping regions. [6,39] Therefore, a possible link can be created to the widely argued transfer effect from one task to another, e.g. music education to improved mathematical skills.[40] This transfer however, exceeds further than only academic achievement in an educational setting. Taken that music highly influences emotional states as well as memory functions it can be incorporated into therapeutic settings, whereby the multisensory nature of music, can stimulate communicative, social or even emotion regulatory traits across clinical as well as neuro typical populations. [12-18]

Tracing the musical stimulus from the auditory nerve to the thalamus and further to the involved brain areas, the superior temporal sulcus (STS) and the superior temporal gyrus (STG) receive direct multisensory input from the thalamic nuclei and are known to be key areas in multisensory processing.[28] These areas stand in direct connection with the frontal lobe, through among others the fasciculus longitudinalis superior and therefore link the incoming stimulus to a complex cognitive exercise. Perceiving, processing and executing music is therefore a complex task, which requires multiple brain areas to compose the understanding of music in the brain.

Understanding these pathways and a more thorough understanding of deeper thalamic functions holds the potential to unravel the mysteries of music perception,

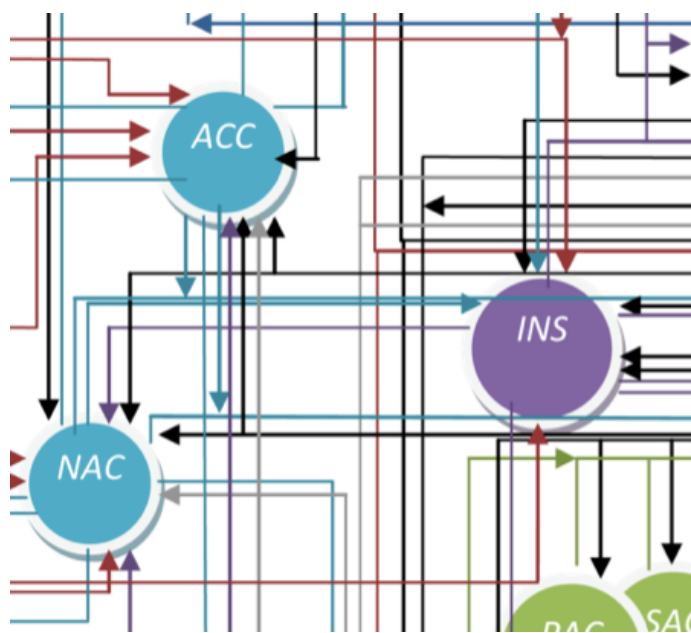


Figure 8: Additional Cortical Areas: ACC (Regulation of activity/experience - listening/playing); INS (Processing emotional aspects); NAC (Dopamine production)

## Discussion

Music touches us quite literally. Once sound contacts the eardrum, the Ossicles translate a mechanical stimulus into an electrical signal, which by passing through the Cochlea and Auditory nerve can be interpreted in the brain. Even though there are multiple studies, which analyse the different effects music can have on individual brain areas, an attempt to

processing and execution in a neural sense. If the Thalamus, as a neural structure, would be left out, together with its multisensory communication abilities, the perception of music may look very different. Physiologically seen, it would miss the connection between the different building blocks that make music. As is hypothesised here, the thalamus combines the different facets of music, with different effects it can have on e.g. cognition, emotion and memory. Multisensory processing of music therefore shares overlapping networks i.e. executive function networks,[41] possibly transferring to mental exercises such as empathy, working memory or inhibition. [6] In line with recent research into thalamic amplification of cortical connectivity to the prefrontal cortex, Schmitt and colleagues [32] have defined an incoming sensory stimulus as a complex cognitive exercise activating multisensory networks. These networks are equally triggered by music, as is presented in the present concept. Music is not just rhythm, or just melody; it is the delicate balance and combination of all the parts that make music, which hold the potency discovered in music therapies and education. [41, 42] Against this backdrop, current research into the building blocks of music (read: rhythm, melody, timber etc.) justifies multisensory integration, as any of these individual building blocks can be seen as one sensory input already activating several networks. Combining these inputs therefore, creates a multisensory input, which requires additional networks and cortical areas, [42] mediated by the thalamus. [32] Consequently, the thalamus holds a much wider role in interpreting and integrating this information, elevating the discussion to 1) single sensory feed-forward distribution of neural networks; 2) feed-back/forward multisensory integration and 3) thalamic feed-forward *music making*.

“Imagine that all musicians playing in an orchestra are connected with thousands of wires, through which, even though they are not speaking to each other, are exchanging signals in all hidden ways (as musicians in an ensemble do), to create a unified sound out of the cacophony of the individual parts. The mapping in our brain works similar to this, with signals traveling back and forth in-between.”

Gerald Edelman [44]

As of yet, more experimental trials and research are needed in the realm of neuroimaging and neurophysiology to analyse the individual nuclei of the thalamus in relation to the multisensory building blocks of music such as melody, rhythm, timber, beat, tone, tonal relationships, intensity and orchestration, as well as the combination of these to support the proposed concept of thalamic multisensory integration. This in turn may shed light into the underlying working mechanisms of music cognition to clinical as well as educational applications. [32,41,42,43]

## Multisensory thalamic integration and the perception and processing of music

Following recent trends in tract tracing studies, increasing evidence supports the view of multisensory processing of incoming stimuli especially stimuli involving complex auditory information.[45,46] Complex auditory information requires next to activation in the auditory cortices, multiple brain networks to be able to process and interpret the stimulus as, in this example, music.[3,4,35,36] Music, with its different facets, therefore can be seen as a multisensory stimulus in light of the above-mentioned diverse response related activations in the brain. When this musical stimulus is traced from the cochlea to all involved brain regions, neural networks lead exclusively through the brainstem and the thalamic nuclei [24,25]. Even though, research has identified these pathways,[39,45] the role of each sub component of music; read melody, timbre, rhythm etc., has not yet been viewed in light of thalamic multisensory integration.

The musical stimulus is split into multisensory levels of perception in the auditory field as well as non-auditory networks. It is this thalamic multisensory integration, which interacts with several cortical and sub-cortical networks as mediated by thalamic pathways before the signal can be interpreted by *us* as music.[47] Acknowledging music as multisensory therefore, moves away from a reductionist point of view and through identifying the intricate network of involved brain areas in the perception of music, it quickly becomes clear, that understanding this stimulus requires simultaneous multiple cognitive and integration processes. [2,23,28,36,39]

## The missing link in existing theories

Against the complexity of music itself, multiple approaches to seeking to understand music have been formed, which may advance our understanding and prompt research of the thalamic multi-sensory integration in music. [15,48] For this purpose, a side-step to language research may shed more light into the matter. Anirud Patel [48] and Isabella Peretz [15] have both simultaneously proposed a theory of sound processing, which are still the most acknowledged in the scientific community. Patel [49,50] has introduced the resource-sharing hypothesis, where all incoming sounds share similar and/or the same cerebral areas in the perception and processing of sound. Sound is defined as any sound, which can be processed and includes music as well as language. Peretz on the other hand has introduced the modularity hypothesis, whereby different incoming sounds (e.g. music or language) have to use different neural structures in order to be processed. Both theories have received equal support throughout the literature and thus no preference to either theory is present as of yet. [50]

Amalgamating all aspects, the role of thalamic multisensory integration in music is to be seen as an expansion on the theories of Peretz and Patel and on neuroscientific models such as the plasticity model,[52] linking networks involved with executive functions as well as emotions, memory or higher order brain functions. Incorporating the increasing understanding of the role the thalamus plays in the perception of music, its' acting can be tested in light of the existing modularity and resource sharing hypotheses. Even though both theories seem fundamentally different, placing thalamic multi-sensory integration at the center of these two hypotheses, a more thorough understanding of music perception is created. Once sound enters the cochlea and is processed via the thalamus and the consecutive brain areas, Patel's resource sharing hypothesis activates areas and networks of incoming sound (*stage 1*). However, through the constant feed forward and feedback loop, the thalamus integrates the perceived sound and divides the stimulus into different sub-components of music or language. Therefore, Peretz's modularity hypothesis forms stage 2 of the musical input as argued in light of tMI (Figure 9).

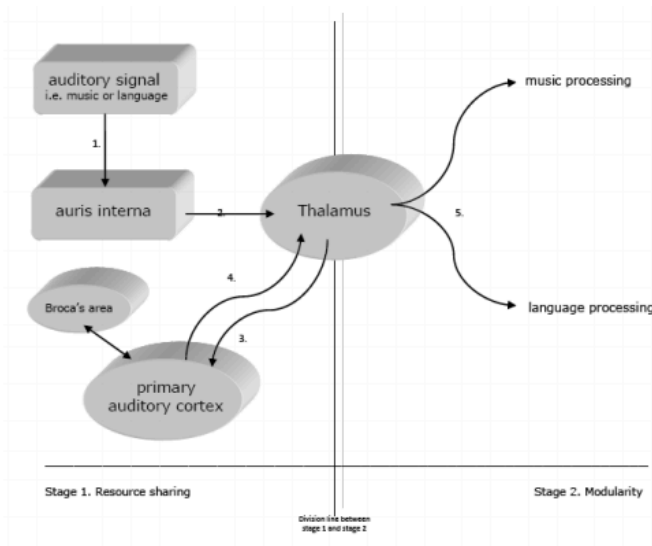


Figure 9: Thalamic multisensory integration at the centre of modularity and resource sharing.

Naturally, thalamic multisensory integration of a multisensory stimulus requires both, stage 1) resource sharing and stage 2) modularity to make sense of the incoming stimulus. These processes are innate to the working of the brain and furthermore support the claim of multisensory integration through the thalamic nuclei in music cognition. [31,32,44] The working of the thalamic nuclei as well as placing it at the centre of two existing theories, remains to be researched through experimental settings, shedding light onto immediate questions: the so far unknown role of the thalamus in higher neural connectivity and

cognition, and furthermore its distinct defining role in music perception, processing and production. [32,36,41,46,51]

### Conclusion

The creation of the here presented neuro-musical map, marks only the beginning of such a categorization and is in no sense considered complete. However, analyzing the connections and the interaction of different brain areas to understand what we perceive as music clears the path to direct implications utilized in music therapy, individual educational approaches or even artificial intelligence and the understanding of deep learning. We intend to spark a discussion on thalamic multisensory integration by introducing this concept. However, additional experimental and clinical investigations in neuroimaging and neurophysiology in music perception, processing and execution will be needed.

At the end, understanding a complex stimulus such as music and the workings of how it functions within the brain, will make the mind susceptible to further questions: nevertheless, it will answer several within its path.

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